Exercises Two and Fifteen are suggested as introductory exercises.

2.5 hours

Geologic Features of Outer Planet Satellites

Instructor Notes

Suggested Correlation of Topics

Comparative planetology, geological mapping, geomorphology, impact cratering, outer planets, tectonism, volcanism

Purpose

This exercise allows the student to develop skills in image interpretation and comparative planetology by analyzing similarities and differences in the landforms and the geological histories of four outer planet satellites. Incorporated are skills of geological mapping, description, and interpretation of tables.

Materials

Clear acetate or overhead projector transparencies (2 sheets per student or group), overhead projector markers (colored markers can be used for added clarity)

Substitutions: Tracing paper, pencils (colored pencils for added clarity)

Background

Reconnaissance of the giant, gaseous outer planets of the solar system and their major satellites was undertaken by the two Voyager spacecraft, launched in 1977. Voyagers 1 and 2 flew past Jupiter and its major satellites in 1979, then explored Saturn and its moons in 1980 and 1981. Voyager 2 flew past Uranus and its satellites in 1986 and explored the Neptune system in 1989. These spacecraft enabled the discovery of the spectacular diversity in the geology of the outer planet satellites.

This exercise uses Voyager images of four of these moons—Ganymede and Io at Jupiter, and Enceladus and Rhea at Saturn—to illustrate this diversity. Most of the outer planet satellites are composed of mixtures of rock and ice. The ice typically is water ice, but more exotic ices, such as methane, are present in some satellites, especially those circling planets farthest from the sun. Io is unusual in being a rocky world, and in the predominance of active volcanism which shapes its surface today. Ganymede and Enceladus show widespread evidence for past volcanism, but the "lava" that once flowed on these satellites is comprised of ice, rather than rock. Ganymede and Enceladus show clear evidence for tectonism, expressed as grooves and ridges. Tectonism has affected Io and Rhea to lesser degrees, and its expression will probably not be apparent to students from the images supplied in this exercise. The most observant students, however, may notice small grooves on Rhea and Io. The abundant cliffs on Io may be tectonic in origin, or they may be related to sublimation of a volatile material and subsequent collapse, a form of gradation.

In general, gradational processes on outer planet satellites are not apparent at the scale of Voyager images and are not specifically addressed in this exercise. However, in discussing the morphologies of craters on Rhea, it would be useful to point out to students that the principal cause of crater degradation on that satellite is the redistribution of material by impact cratering. New craters pelt older ones, creating ejecta and redistributing material to subdue the forms of fresh craters over time. To a lesser extent, mass wasting probably acts to modify crater shapes through the action of gravity.

There are many opportunities for class discussion of specific topics only touched upon by this exercise. For example, question 5 regarding the morphologies of craters on Ganymede might initiate discussion on what could cause their different appearances. Where relevant, information that will help the instructor guide discussion is included in square brackets within the answer key.

It may be interesting to consider the sources of heat for driving the volcanism and tectonism on outer planet satellites. The gravitational pull on a satellite by the parent planet about which it orbits and by neighboring satellites can cause tidal heating of the satellite. Heat is generated as the satellite is squeezed by gravitational stress as it moves in a slightly elliptical orbit about its primary planet. This is the principal source of heat for Io, and may have driven activity on Ganymede and Enceladus in the past. Rhea has been relatively inactive; however, poor resolution Voyager views of Rhea's opposite hemisphere provide tantalizing hints that volcanism and tectonism indeed have affected Rhea to some extent.

The instructor may choose to show Voyager images of other icy satellites, such as Iapetus, a moon of Saturn that shows one bright, icy hemisphere while its other half is as dark as charcoal; Miranda, a moon of Uranus that shows spectacular regions of volcanism and tectonism juxtaposed within ancient cratered terrain; or Triton, Neptune's large moon which has active geysers likely propelled by liquid nitrogen that shoots up into a tenuous atmosphere. Also, this exercise has neglected enigmatic Titan, the largest moon of Saturn, which possesses an atmosphere of nitrogen, methane, and organic compounds so thick as to hide its surface. Pluto and its satellite Charon have not yet been visited and photographed by spacecraft. These two objects are small and icy, akin to many outer planet satellites; thus, information about them is included in Table 1.

This exercise is designed for individual completion by each student. Instructors may wish to have students work together in groups, perhaps with each student of a group being responsible for a specific satellite. Where relevant questions are encountered, encourage students to separate their *description* of a satellite surface from their *interpretation* of the geological history of the surface; questions here attempt to distinguish the two. Note that some questions ask for the student to report a radius value when given a satellite's diameter, requiring some simple math.

If the mapping exercises are done on clear acetate as recommended, then they can be overlain on an overhead projector to compare student maps and prompt discussion of mapping choices. The final question (number 20) works well when done together as a class discussion. It may be useful for the class to construct a chart that summarizes the radii, densities, and compositions of each satellite (compiling information from questions 1, 6, 11, and 16). This will facilitate discussion of how these parameters might affect satellite activity. It will be found, however, that there are no obvious correlations from the satellites introduced in this exercise.

It would be useful to review with students the processes of impact cratering, volcanism, and tectonism (as introduced in Unit One) before proceeding with this exercise. Discussion of geologic mapping and stratigraphic relations (introduced in Unit 5) would be helpful as well. Exercise 10 is a good complement to this one, as it investigates the terrestrial planets at the global scale.

Science Standards

- Earth and Space Science
  - Origin and evolution of the Earth system

Mathematics Standards

- Computation and estimation

Answer Key

I. Ganymede

1. Ganymede orbits the planet *Jupiter*. Its radius of *2631* km makes it the largest satellite in the solar system, bigger even than the planet Mercury. Its density of *1.94* g/cm^3 means that it is composed of a *roughly equal mixture of rock and ice.*

2. **a.** The bright terrain has a high albedo and shows few craters. It contains sets of parallel and intersecting grooves, and also shows smooth areas. Some of the bright material is contained within narrow lanes that cut across the dark terrain.

   b. The dark terrain has a low albedo and shows many craters. Few grooves are seen on the dark terrain. The dark terrain can form "islands" within the bright terrain.

3. **a.** The dark terrain is older, as it is the more heavily cratered and is cross-cut by swaths of bright terrain.

   b. Although the ages of individual crater ejecta deposits will vary depending on the age of a crater, ejecta from crater "A" is superimposed on both bright and dark materials, indicating that the ejecta is younger than these other materials.

4. The bright terrain includes smooth patches and is only lightly cratered, suggesting that it is volcanic in origin and that bright terrain volcanism probably erased preexisting dark terrain craters. The bright terrain contains numerous grooves, which are probably of tectonic origin. [The grooves probably formed by extensional tectonism (rifting), meaning that the bright material was pulled apart, and fault valleys formed the grooves.]

5. **a.** This 100 km diameter crater shows a central dome. [Crater domes might form in large craters either by rebound upon impact or from later magmatism.] It also shows very small craters around it, some aligned in chains. [These smaller craters are secondaries—formed as chunks of ejecta were thrown from the large crater as it formed.]

   b. This 23 km diameter crater shows bright rays emanating from it. [Bright rays are created by ejecta thrown from relatively fresh craters, and they disappear over time as subsequent smaller impacts pelt this material.]

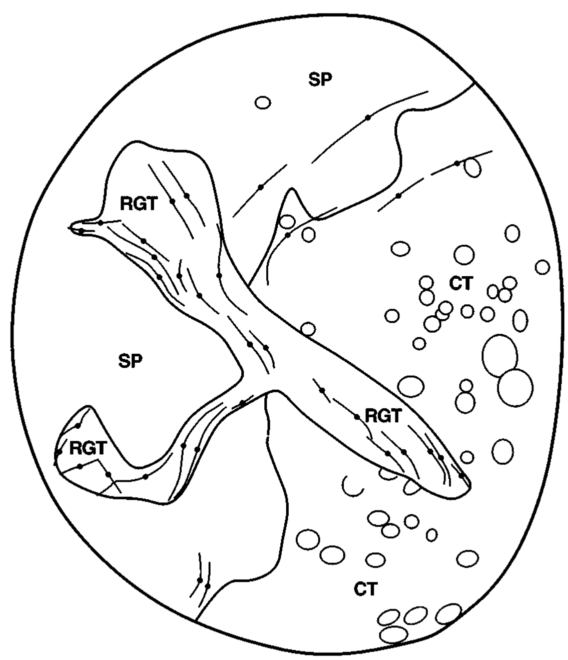
   c. This 50 km crater has been cut by a dark terrain groove.

   d. This 10 by 60 km feature is probably an impact crater that formed by an oblique (low angle) impactor which skimmed the surface of Ganymede as it hit. [Students may notice that some craters in the bright material have dark floors. Dark craters can form in bright material either because the impactor was a dark asteroid rather than a bright comet, or because the craters punch through bright material to throw out underlying dark material in their ejecta.]

II. Enceladus

6. Enceladus orbits the planet *Saturn* and has a radius of only *251* km. Its density of *1.24* g/cm^3 means that it is composed of *mostly ice*. Its albedo of *95%* is *higher* than the albedo of any other satellite.

7. The largest craters on Enceladus show central mounds. [The mounds might be due to central volcanism or slow rebound of the crater shape because of a warm satellite interior.] Some medium-sized craters in the bottom third of the image appear to have been cut in half. [They were probably disrupted by tectonism and/or partially flooded by volcanism.]



Geologic Sketch Map of Enceladus

Answer Key (continued)

8. Grooves and ridges are predominantly concentrated in a band that runs across the satellite.

9. (Answers will vary)

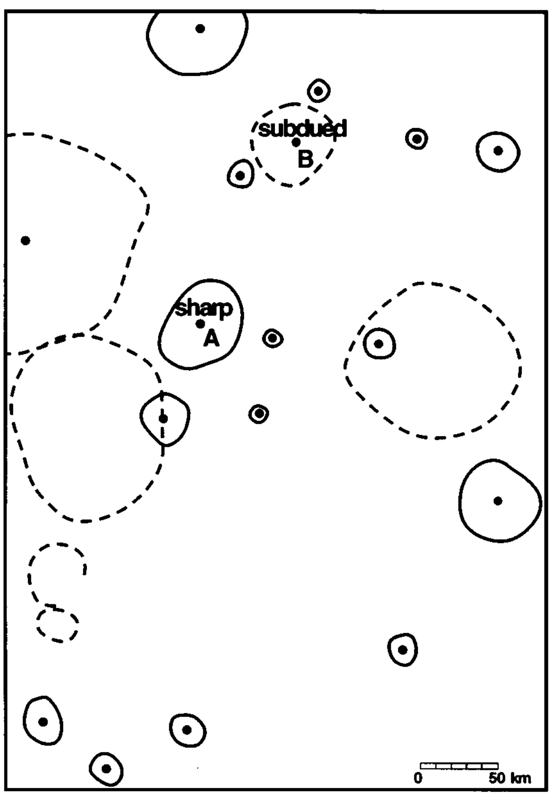
   a. *Cratered terrain:* Characterized by numerous craters, with few obvious grooves.

   b. *Ridge-and-groove terrain:* Characterized by approximately parallel-trending ridges and grooves that curve gently and has few craters.

   c. *Smooth plains:* Smooth-appearing plains with little evidence for topography other than a few tectonic features.

10. **a.** The cratered terrain is oldest, as it is the most heavily cratered and it appears to be cross-cut by the ridge-and-groove terrain.

    b. It is difficult to be certain of the relative ages of the smooth plains and the ridge-and-groove terrain. The smooth plains may be the youngest, having flooded the region neighboring the ridge-and-groove terrain. On the other hand, preexisting smooth plains may have been tectonically deformed to create the ridge-and-groove terrain. (Answers will vary.)



Rhea Crater map

III. Rhea

11. Rhea orbits the planet *Saturn* and has a radius of *764* km. Its density of *1.33* g/cm^3 means that it is composed of *ice with minor amounts of rock.*

12. Impact cratering.

13. **a.** (See question 14.a. below.)

    b. (See question 14.a. below.)

    c. Craters probably have sharp-appearing morphologies when they first formed, i.e., when they were "fresh." Over time, craters become more and more subdued or "degraded."

14. **a.** [Because subdued craters may be difficult to find, several are indicated on this sketch map.]

    b. Central peaks are more apparent in fresh craters.

    c. The fact that peaks are most apparent in fresh craters suggests that central peak topography, like the rest of the crater, becomes more subdued and less prominent over time as subsequent impacts redistribute material.

    d. The transition diameter is between ~10 and 20 km.

15. **a.** Rhea shows abundant evidence for cratering, and is more heavily cratered than the surfaces of the other two satellite. Unlike Ganymede and Enceladus, this part of Rhea shows no smooth terrains and essentially no grooves. Like Enceladus, Rhea's surface is of uniform albedo; this is in contrast to the surface of Ganymede, which shows bright and dark terrains.

    b. Rhea has had a less active geological history. It is dominated by the external process of cratering. Unlike Ganymede and Enceladus, it does not show widespread evidence for the internally-driven processes of volcanism and tectonism.

IV. Io

16. Io is a satellite of the planet *Jupiter.* Its density of *3.57* g/cm^3 means that it is composed of *rock.* This density is unusual in that it is *higher* than that of any other outer planet satellite. Io is *1815* km in radius.

Answer Key (continued)

17. **a.** Volcanism.

    b. It shows a somewhat irregular, scalloped shape of three coalescing circles.

    c. A caldera.

18. Volcanism is the principal process shaping the surface of Io, as demonstrated by the abundance of flow-like features, smooth materials, and irregularly-shaped calderas that are commonly associated with high and/or low albedo materials. No impact craters can be confidently identified on Io, and they have presumably been erased by volcanism.

19. Craters on Rhea are a) generally more circular; b) more numerous; c) commonly have smaller craters superimposed on them; d) show a range of morphologies from sharp to subdued (a range of degradation states); e) show central peaks. Some craters on Io are associated with bright and/or very dark materials.

20. (Answers may vary—acceptable alternative answers are provided in parentheses.)

	Ganymede	Enceladus	Rhea	Io
Impact Cratering	**2 (3)**	**3 (2)**	**1**	**4**
Volcanism	**3 (2)**	**2 (3)**	**4**	**1**
Tectonism	**1 (2)**	**2 (1)**	**4 (3)**	**3 (4)**

Name ______________________________

Geologic Features of Outer Planet Satellites

Purpose

To recognize the similarities and differences in the processes affecting the outer planet satellites, and in the resulting landforms.

Materials

Acetate (2 sheets), overhead transparency markers

Introduction

Planetary geologists study the solid surfaces of solar system objects. This includes the planets of the inner solar system and the moons, or **satellites**, of all the planets. The giant gaseous planets of the outer solar system—Jupiter, Saturn, Uranus, and Neptune—have a total of 62 satellites.

The outer planets are far from the warmth of the Sun, so the satellites that circle them are very cold—so cold that many are composed partly or mostly of **ice**. Much of the ice in these satellites is water ice, the kind in your freezer. But some satellites probably contain other types of ice, including ammonia, methane, carbon monoxide, and nitrogen ices. These are compounds that you may know as liquids or gases in the warm environment of Earth.

Some outer planet satellites display many **impact craters**, and some are less cratered. In general, an older surface shows more and larger impact craters than a younger surface. Also, younger features and surfaces will cut across or lie on top of older features and surfaces. Relatively fresh or large craters commonly show a blanket of bright **ejecta**, material thrown from the crater as it was formed.

The surfaces of outer planet satellites can also be shaped by **volcanism** and **tectonism**. Volcanism can erase craters while creating regions that appear smooth. On a rocky satellite, the volcanic lava will be rocky; on an icy satellite, an icy or slushy "lava" might emerge from the satellite's relatively warm interior. A centers of volcanism is sometimes marked by an irregularly shaped volcanic crater termed a **caldera**. Tectonism can create straight or gently curving grooves and ridges by faulting of the surface. Commonly, an area smoothed by volcanism will be concurrently or subsequently affected by tectonism. A volcanic or tectonic feature must be younger than the surface on which it lies.

The **density** of a planet or satellite provides information about its composition. Density is a measure of the amount of mass in a given volume. Rock has a density of about 3.5 g/cm^3, and most ices have a density of about 1 g/cm^3. This means that a satellite with a density of 3.5 g/cm^3 probably is composed mostly of rock, while a satellite of density 1 g/cm^3 is composed mostly of ice. A satellite with a density of 2 g/cm^3 probably is composed of a mixture of nearly equal amounts of rock and ice.

The **albedo** of a satellite is a measure of the percentage of sunlight that the surface reflects. A bright satellite has a high albedo, and a dark satellite has a low albedo. Pure ice or frost has a very high albedo. If a satellite's surface is icy but has a low albedo, there is probably some dark material (such as rock) mixed in with the ice.

Even if the albedo of a satellite is completely uniform, the apparent brightness of the surface can change based on the positions of the Sun and the observer. The lit edge, or **limb**, of a planet or satellite typically appears bright. The surface looks darker as the day/night line, or **terminator**, is approached because that is where shadows are longest.

Properties of the Major Satellites* of the Solar System and Pluto

Planet	Satellite	Diameter (km)	Mass ($x10^{23}g$)	Density (g/cm^3)	Albedo (%)
Earth	Moon	3476	735	3.34	12
Jupiter	Io	3630	894	3.57	63
	Europa	3138	480	2.97	64
	Ganymede	5262	1482	1.94	43
	Callisto	4800	1077	1.86	17
Saturn	Mimas	394	0.38	1.17	60
	Enceladus	502	0.8	1.24	95
	Tethys	1048	7.6	1.26	70
	Dione	1118	10.5	1.44	50
	Rhea	1528	24.9	1.33	60
	Titan	5150	1346	1.881	20
	Iapetus	1436	18.8	1.21	4 (leading), 50 (trailing)
Uranus	Miranda	492	0.69	1.15	32
	Ariel	1158	12.6	1.56	31
	Umbriel	1170	13.3	1.52	20
	Titania	1578	34.8	1.70	28
	Oberon	1522	30.3	1.64	23
Neptune	Triton	2706	214	2.07	73
	Proteus	416	~0.4?	~1.5?	6
Pluto		~2360	~130	~2	~50
	Charon	~1180	~110	~1.3	~40

* Only satellites larger than about 400km diameter are listed here, in order of increasing distance

Questions and Procedures

I. Ganymede

1. The Table will help you to fill in the blanks:

   Ganymede orbits the planet____________. Its radius of _______ km makes it the largest satellite in the solar system, even bigger than the planet Mercury. Its density of ______ g/cm^3 means that it is composed of____________ .

Examine Figure 13.1a, which shows part of the Sippar Sulcus region of Ganymede, and compare what you see to the **geomorphic** sketch map of the area (Figure 13.1b). Notice that the surface of Ganymede can be divided into two principal geologic units, bright terrain and dark terrain. The dark terrain is believed to be a mixture of ice and rock, while the bright terrain is probably composed mostly of ice.

2. List and describe the many characteristics of the bright and dark terrains. Be as detailed as possible. Include factors such as albedo, number of craters, general surface appearance, and other characteristics that are apparent.

   a. bright terrain:

   b. dark terrain:

3. **a.** Which of Ganymede's two principal terrain types is older? How can you tell?

   b. What is the age of the ejecta for the crater marked "A" relative to the bright and dark terrain? How can you tell?

4. Many researchers believe that the bright terrain of Ganymede was shaped by both volcanism and tectonism. What is some evidence that this is true?

5. All the craters you can see in Figure 13.1a probably formed by the impacts of comets or asteroids. Many show small central pits, created as a result of impact into an icy target.

Four craters that show unusual morphologies are indicated in Figure 13.1b with the letters **A** through **D**. Describe the shapes and characteristics of these interesting craters. Include the *dimensions* of each crater using the scale bar, and also describe the *characteristics* that make it peculiar compared to most other craters on Ganymede.

A: ____

____

____

B: ____

____

____

C: ____

____

____

D: ____

____

____

II. Enceladus

6. Enceladus orbits the planet __________ and has a radius of only _______ km. Its density of_______-g/cm^3 means that it is composed of __________ ____________________. Its albedo of __________ is __________ than the albedo of any other satellite.

Now make a geological sketch map of Enceladus. Use as a guide the map of Ganymede in Figure 13.1. Tape a piece of acetate over the photograph of Enceladus, Figure 13.2. Trace the outline of the satellite. You will find that it is simple to trace the satellite's limb, but the terminator is not as clearly defined. Next, outline the most prominent craters on the satellite, you will have to decide which craters should be included.

7. Locate and describe two unusual looking craters.

   Grooves on Enceladus are probably tectonic features; next map their locations. This symbol (-●-) is one way of mapping a groove. Draw a thin line along each groove you see, and place a dot near the center of each line to indicate it is a groove.

8. Where do grooves (and the ridges between them) occur on Enceladus?

The surface of Enceladus can be divided into three different types of terrain. Think about the features you have mapped so far, and decide on how to divide the surface into three terrains. Decide on names that describe your units. (For example, “cratered terrain.”)

Draw boundaries around the different units. There might be only one patch of each unit, or there could be more than one patch. To complete the map of Enceladus, label the units with the descriptive names that you have given them.

9. List the names of your three units. Following each name, describe the characteristics of each unit as *you* defined it in making your map of Enceladus.

   A: ____

   ____

   ____

   B: ____

   ____

   ____

   C: ____

   ____

   ____

10. **a.** Which is the oldest of these three major units on Enceladus? How can you tell?

    b. Which is the youngest of these three major units on Enceladus? How can you tell?

III. Rhea

11. Rhea orbits the planet __________ and has a radius of _______ km. Its density of ______ g/cm^3 means that it is composed of _____________________.

12. Examine Figure 13.3, which shows a part of Rhea's surface. What is the principal geologic process that has shaped this part of Rhea?

13. Notice the **morphologies** (shapes) of the craters that you see in Figure 13.3. The 60 km crater **A** shows a sharp and distinct morphology, with steep and well-defined slopes. On the other hand, the 65 km crater **B** is more difficult to identify, as it is rounded and indistinct. Keep in mind that the cratered surface of Rhea seen is probably about 4 billion years old.

    a. Lay a piece of acetate over Figure 13.3, taping it at the top. Trace the rectangular outline of the photo, and also trace and label the scale bar. With a solid line, trace the outline of crater A, and label the crater “sharp.” Next locate and trace the outline of crater B, but this time use a dashed line. Label this crater “subdued.”

    b. Locate one additional sharp crater, outlining it with a solid line. Find an additional subdued crater, and outline it with a dashed line.

c. The terms "sharp" and "subdued" are descriptive terms, used to describe the morphologies of craters. Sharp-appearing craters are sometimes referred to as "fresh," while subdued-appearing craters are commonly referred to as "degraded." What do the terms "fresh" and "degraded" imply about how a crater's morphology changes with time on Rhea?

14. Notice that some of Rhea's craters, including crater **A**, show central peaks. These form upon impact, due to rebound of the floor during the "modification stage" of the cratering process.

a. On the acetate, outline as many central peak craters as you can confidently identify. Retain the scheme of outlining each sharp crater with a solid line, and each subdued crater with a dashed line. Put a dark dot in the middle of each central peak crater that you identify.

b. Are central peaks more recognizable in sharp or subdued craters?

c. Based on your answer to part b, what can you infer about how the topography of a central peak changes over time?

d. Central peaks form only in craters above a certain diameter. This "transition diameter" from simple, bowl-shaped craters to more complex, central peak craters depends on surface gravity and material properties, so it is different for each planet and satellite. Estimate the transition diameter for craters on Rhea based on the smallest central peak craters that you are able to identify.

15. Consider the surface of Rhea (Figure 13.3) in comparison to the surfaces of Ganymede (Figure 13.1) and Enceladus (see Figure 13.3 and your sketch map).

a. Compare and contrast the general appearance of the surface of Rhea to the surfaces of Ganymede and Enceladus.

b. What do the differences in surface appearance suggest about the geological history of Rhea as compared to the histories of Ganymede and Enceladus?

IV. Io

16. Io is a satellite of the planet __________. Its density of ______ g/cm^3 means that it is composed of _____________________. This density is unusual in that it is ___________ than that of any other outer planet satellite. Io is _____________ km in radius.

Examine Figure 13.4, which shows part of the surface of Io. The very high albedo material is considered to be sulfur dioxide frost. When the two Voyager spacecraft flew by Io in 1979, they photographed nine actively erupting volcanoes.

17. Examine the feature in the far northeast corner of the image, which shows a central depression with relatively low albedo (dark) material radiating from it.

a. What process created this feature?

b. Describe in detail the shape of the central depression. Use a sketch if you like. (Use the sketch area below.)

Sketch area

c. What kind of volcanic "crater" is this central depression?

18. Examine the other craters and surface features seen in Figure 13.4. What is the principal process shaping the surface of Io? List some observations that support your answer.

19. Contrast the characteristics of craters that you see on Io to those on Rhea. List at least four differences between Io's volcanic craters and Rhea's impact craters.

20. On the chart below, rank the relative importance of impact cratering, volcanism, and tectonism on the four outer planet satellites that you have studied, based on the images you have seen. Use numbers from 1 (for the satellite most affected) to 4 (for the satellite least affected).

	Ganymede	**Enceladus**	**Rhea**	**Io**
Impact Cratering				
Volcanism				
Tectonism				

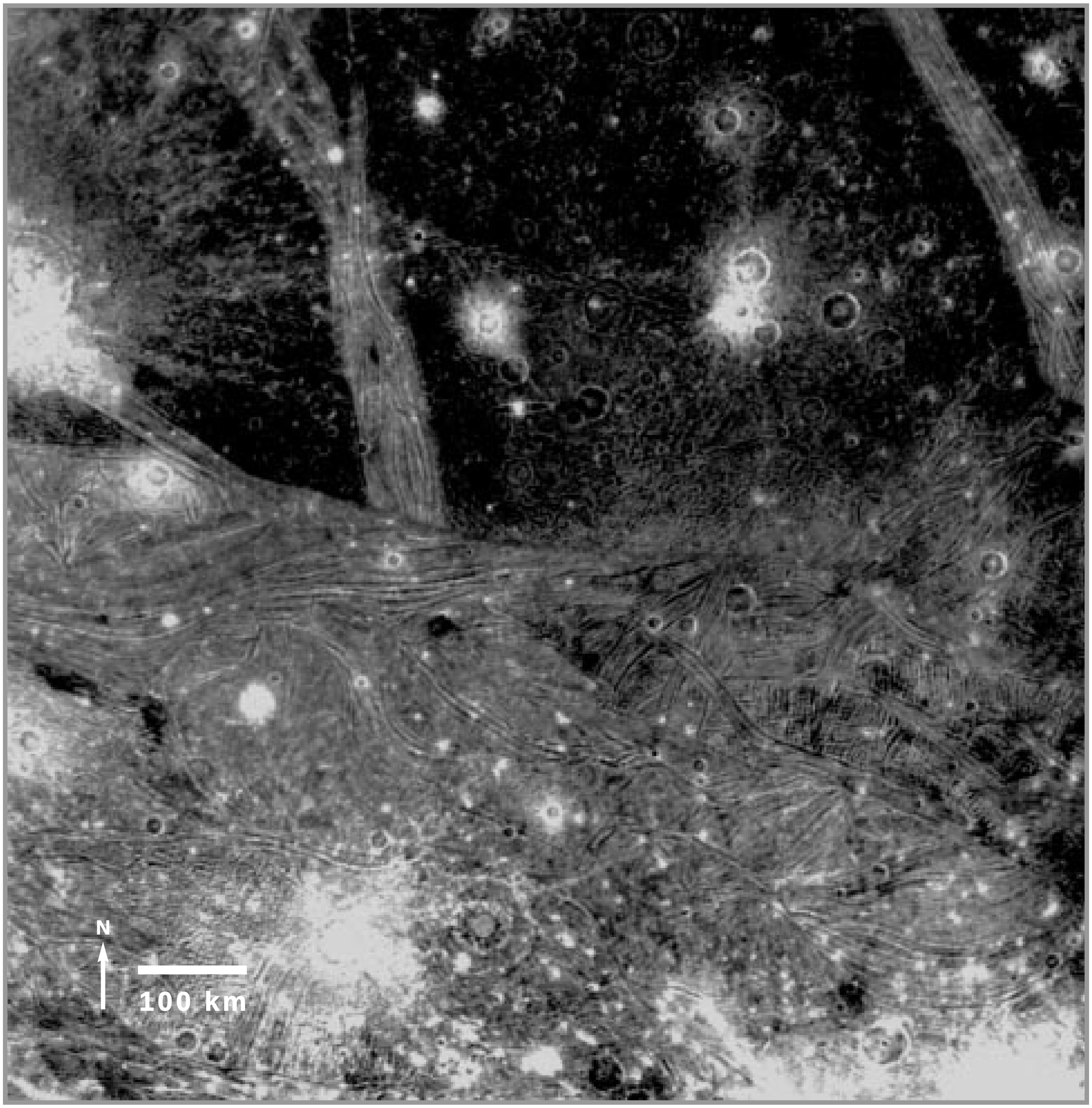


Figure 13.1.a. *Voyager 2 image of Ganymede (FDS 20636.02) at a resolution of 1.5 km/pixel, showing part of Sippar Sulcus in lower half.*

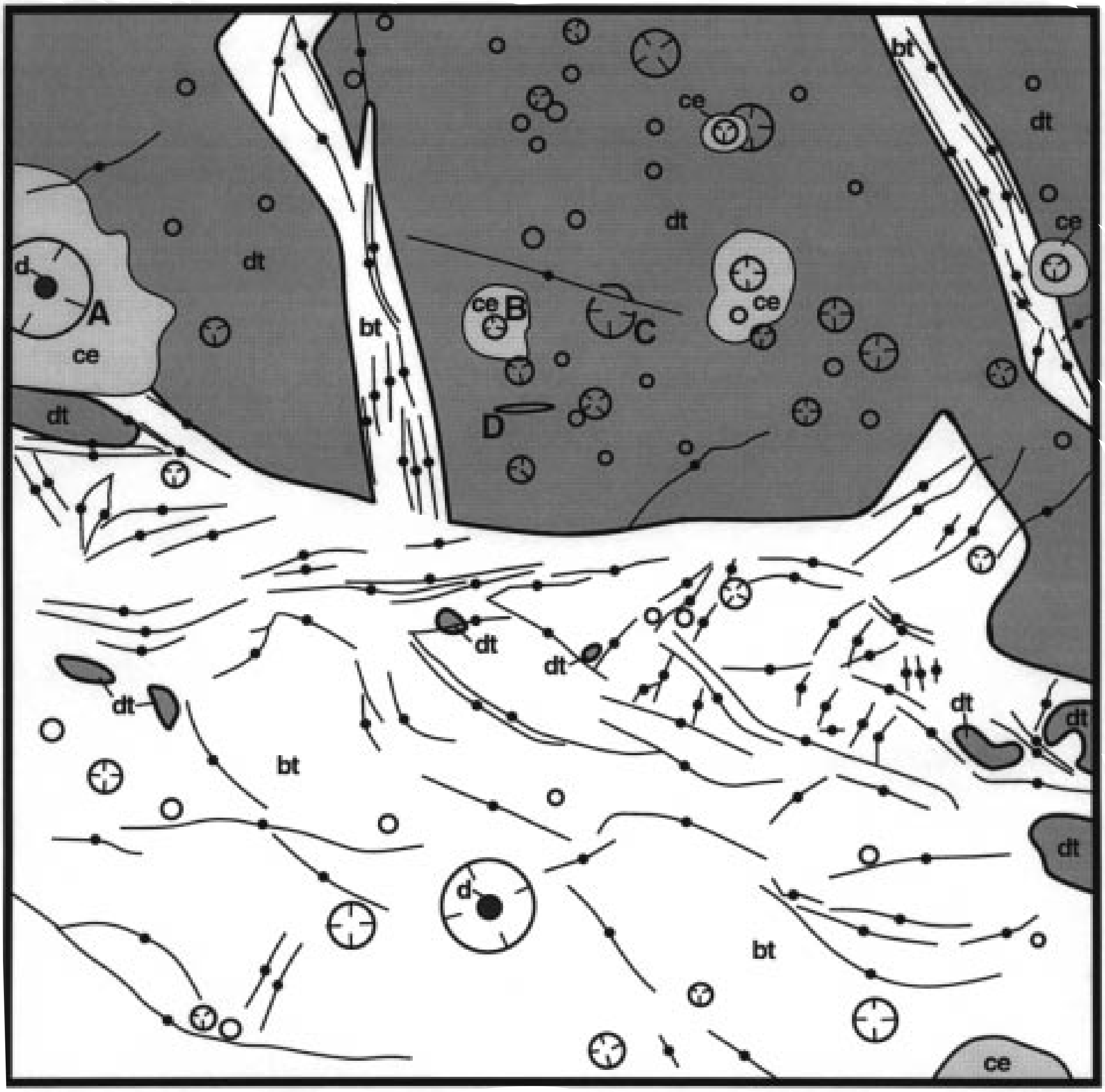


Figure 13.1.b. *Geological sketch map corresponding to Figure 13.1a.*

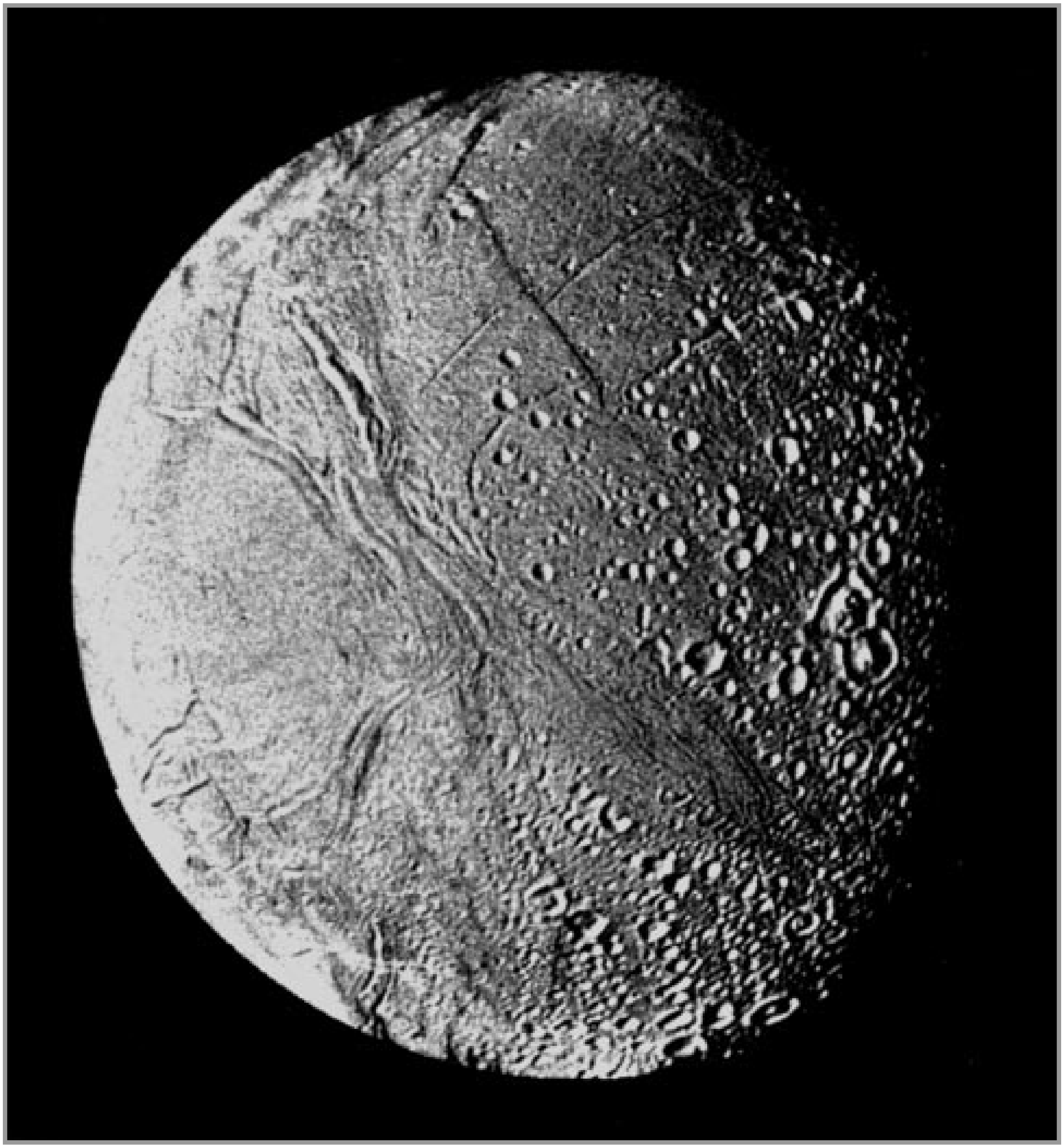


Figure 13.2. *Photomosaic of Enceladus constructed from Voyager 2 images with resolutions of about 2 km/pixel. The satellite has a diameter of approximately 500 km. (Jet Propulsion Laboratory photomosaic P-23956 BW).*

Figure 13.3. *The surface of Rhea, seen by Voyager 1 at 700 m/pixel (FDS 34952.59).*

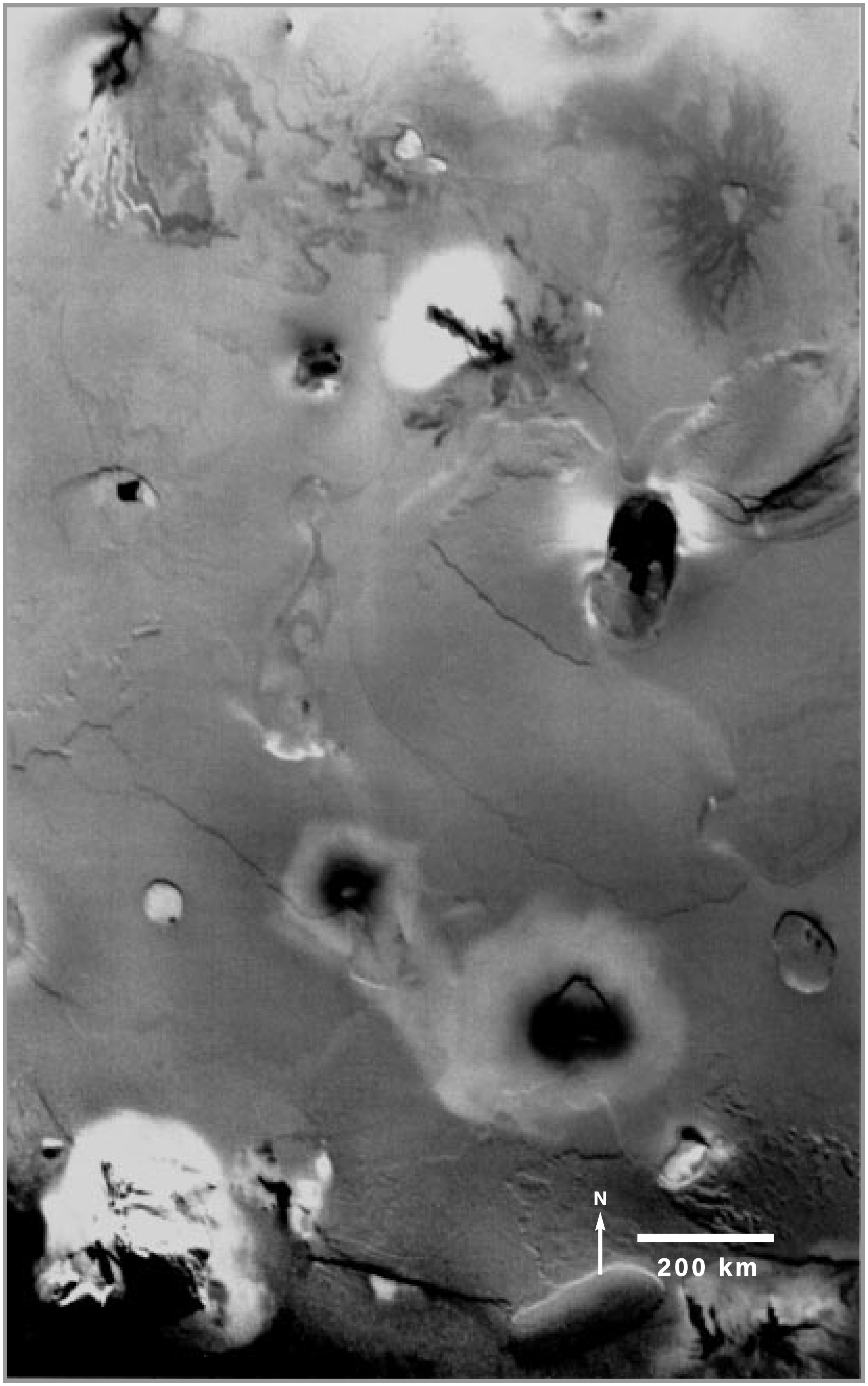


Figure 13.4. *The surface of Io seen in a mosaic of Voyager images FDS 16392.43, .39, and .41. Resolution is 2.1 km/pixel. (United States Geological Survey mosaic V0357/1).*